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The study of detachment and deposition on a hillslope using a magnetic tracer

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Abstract

Soil erosion by water involves the processes of detachment, transport and deposition of soil materials by the erosive forces of raindrops and surface flow of water. The redistribution of sediment within a field-sized area is important in estimating the effect of erosion and deposition on productivity, in helping the conservation planner to target efforts to reduce erosion, and to evaluate erosion models. The objective of this study was to use a magnetic tracer, with size and density similar to soil aggregates, to study detachment and deposition on a hillslope. Two interconnected plots were established on a hillslope. Two rainfall intensities (35 and 70 mm h^{-1}) combined with two different inflow rates (4 and 10 l min^{-1}) were applied to the upper of the two plots. No rain or water was applied to the lower plot, which was used to study the deposition of eroded sediments from the upper plot. A 5% concentration of magnetic tracer was placed in the upper plot and mixed to depth of 3 cm. From this initial condition, areas of tracer detachment and deposition were identified using a magnetic sensor. Areas of detachment were associated with a decrease in magnetic signal, while areas of deposition were associated with an increase in the magnetic signal. In the lower plot, deposition of tracer correlated well with the magnetic susceptibility readings. Results indicated that the tracer was effective for identifying areas of net detachment and deposition, however, the tracer to soil ratio did not remain constant for all treatments. For this reason, a wider range of sizes and densities of the tracer should be tested if the method is to be useful to quantify erosion rates.

Keywords: Soil erosion; Sediment; Deposition; Rainfall simulator; Tracer

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1. Introduction

Soil erosion by water is considered a process involving the detachment, transport and deposition of soil materials by the erosive forces of rainfall and surface flow of water (Ellison, 1947). Detachment, transport and deposition occur simultaneously on hillslopes, where evaluations of soil erosion have normally been made on plots of uniform slopes using rainfall simulators or natural rainfall (Mutchler et al., 1994). The standard soil erosion–runoff plots (Wischmeier and Smith, 1978) provide data on the average rates of soil erosion in the form of total amount of soil loss from the study area. However, no information is provided on the origin of the soil materials nor on the spatial and temporal variations of detachment and deposition within the area of evaluation. Accurate evaluations of the processes of detachment, transport and deposition from hillslopes are important to better understand the process of soil erosion and to evaluate and validate physically based erosion models.

Soil detachment and deposition has been studied using various techniques. The analysis of radio-nuclides such as ^{137}Cs within the landscape has been used as a method for assessing long-term soil erosion and net deposition at various spatial scales and in a wide range of environments (Walling and He, 1999). Ritchie et al. (1974) described a method for using measurements of the percentage loss of fallout ^{137}Cs to measure soil loss. After being released to the environment by nuclear tests or nuclear reactors, ^{137}Cs is strongly adsorbed on clays and organic particles and is essentially non-exchangeable. Its measurement is relatively easy and accurate, but the values obtained normally represent long-term average values of soil erosion and deposition (Walling and Quine, 1991).

Cosmogenic nuclides, such as ^{10}Be, have also provided a new method for inferring erosion rates by revealing how long mineral grains have been exposed to cosmic rays near the landscape surface (Granger et al., 1996). Similar to ^{137}Cs, ^{10}Be is delivered to the earth surface primarily by rain, then, it is absorbed on the soil and other surficial minerals, preferentially on clay and organic matter. The affinity of ^{10}Be for near surface particles enables its use as a tracer of soil erosion (Valette-Silver et al., 1986). This method has been used to identify areas of accelerated erosion in dynamic landscapes of the eastern United States (Brown et al., 1995).

The use of rare earth elements (REE) has been presented as an alternative to the use of ^{137}Cs and ^{10}Be, which are mostly for medium- and long-term estimations of soil loss. Junliang et al. (1994) used REE to study the spatial distribution of soil erosion intensity and the deposition rate of eroded materials. REE adsorb quickly on soil particles, are insoluble in water and represent no potential environmental or toxicity problems. REE can be measured by analytical techniques to a high level of sensitivity, however, the cost of the determinations represent an economic limitation. There has not been an extensive research on the use of REE to study soil erosion.

Although mostly used for tracing sediments in rivers and reservoirs, the magnetic properties of sediments is another method reported in soil erosion studies (Caitcheon, 1997). This method is based on the relative contribution of natural magnetic minerals in sediments and gives information on the origin of them if the sources are identified. Ventura et al. (2001) developed a soil erosion tracer consisting of magnetized round particles, which were made of polystyrene beads embedded with magnetite powder. The final magnetic tracer has a density and size similar to soil aggregates. When mixed with soil at a given ratio and subjected to simulated rainfall, the tracer has been shown to move in phase with the soil, making tracing of particles possible with a magnetometer. The magnetic tracer technique has advantages over the other techniques since it is inexpensive, non-intrusive, non-destructive and it does not use radioactive materials.

The objective of this study was to use a magnetic tracer to study spatial variations of soil detachment and deposition on hillslopes under different rainfall intensities and runoff rates and to identify areas where those processes occur.

2. Materials and methods

Field plots were used to obtain experimental data for evaluating soil erosion and the redistribution of sediments on hillslopes using a magnetic tracer, a magnetic sensor, and a programmable rainfall simulator coupled with a water inflow supplier used to add surface water inflow to the upper end of the plot.

The experiment was conducted at Purdue University's "Throckmorton Farm" located 25 miles southeast of Lafayette, IN on a field with an average slope of 5%. The soil, typical of the area, belongs to the "Miami" series and is classified as fine-loamy, mixed, mesic Oxyaquic Hapludalf (Dontsova, 1998). Bulk density of this soil was approximately 1.3 Mg m^{-3}. Before setting up the experiment, residues were removed from the surface and the soil was tilled with a hand-operated tiller to a depth of 20 cm. The experimental setup consisted of two plots interconnected down the slope (Fig. 1). Plywood sheets (as opposed to metal) were used to build the edges of the plots to avoid interference with the magnetic sensor. Plot 1 (1 × 6 m) was located up-slope and used as source of sediment and to study the combined effect of rill and interrill erosion. The magnetic tracer developed by Ventura et al. (2001) was placed in this plot mixed to a depth of 3 cm and a concentration of 5% by weight. The magnetic tracer consisted of polystyrene beads with magnetite powder embedded via a heating process. They had a mean weight diameter (MWD) of 3.2 mm and a density of 1.21 g cm^{-3}. Plot 2 (0.5 × 8 m) was located downslope and was used as an area of deposition of sediments and tracer transported out from the upper plot. The lowest limit of plot 2 ended on a grass strip. No magnetic tracer was placed initially in this lower plot (Fig. 1).

A programmable rainfall simulator (Niebling et al., 1981) was used to apply simulated rainfall to plot 1 at two different intensities (35 and 70 mm h^{-1}) combined with two different inflow rates (4 and 10 l min^{-1}). The combination totaled four treatments, which were replicated twice. Each hydraulic treatment was applied until steady state conditions were achieved in the runoff rate. No rain or inflow was applied to plot 2. However, all the runoff produced from plot 1 was conducted to plot 2 continuously, except for the break time necessary to take runoff and sediments samples directly from the upper plot. Deionized water was used to simulate as closely as possible the chemistry of natural rainfall.

The magnetic readings were done using the MS2 magnetic susceptibility meter coupled with the MS2D probe or sensor (Ventura et al., 2001). Readings were taken on the soil surface in both plots following a grid with 20 × 20-cm cells. Magnetic susceptibility (χ) for this instrument is reported in non-dimensional SI units, expressed as units × 10^{-5} SI,

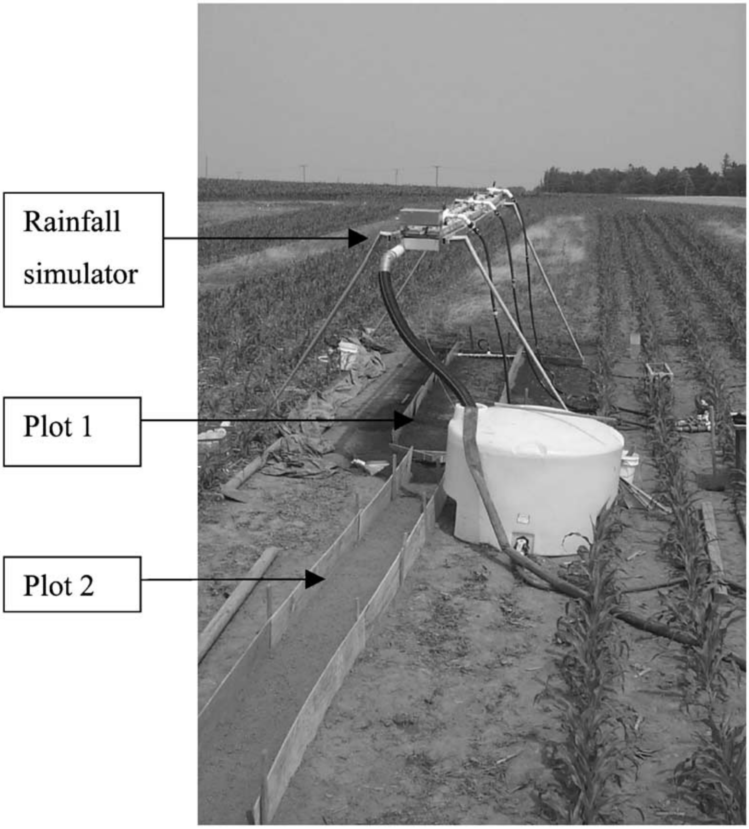

Fig. 1. Experimental setup. Rainfall and inflow were applied in plot 1. Plot 2 was used to study deposition of sediments from plot 1.

(Dearing, 1994). Measurements of the background soil magnetic susceptibility were made immediately prior to adding the magnetic tracer, and immediately after its addition to quantify the increase due to the magnetic tracer. The second set of readings was considered as initial conditions before application of the hydraulic treatments. Magnetic readings were taken after each treatment in both the erosion and deposition plots to locate areas of detachment and deposition. The comparisons were made within the 20 × 20-cm grid cells, which is approximately the diameter (18.5 cm) of the loop of the MS2D probe, over the entire experimental area.

During the experiments, runoff and sediment samples were collected from the runoff of plot 1 every 5 min in 1-l wide-mouth bottles after runoff initiated. The total weight was

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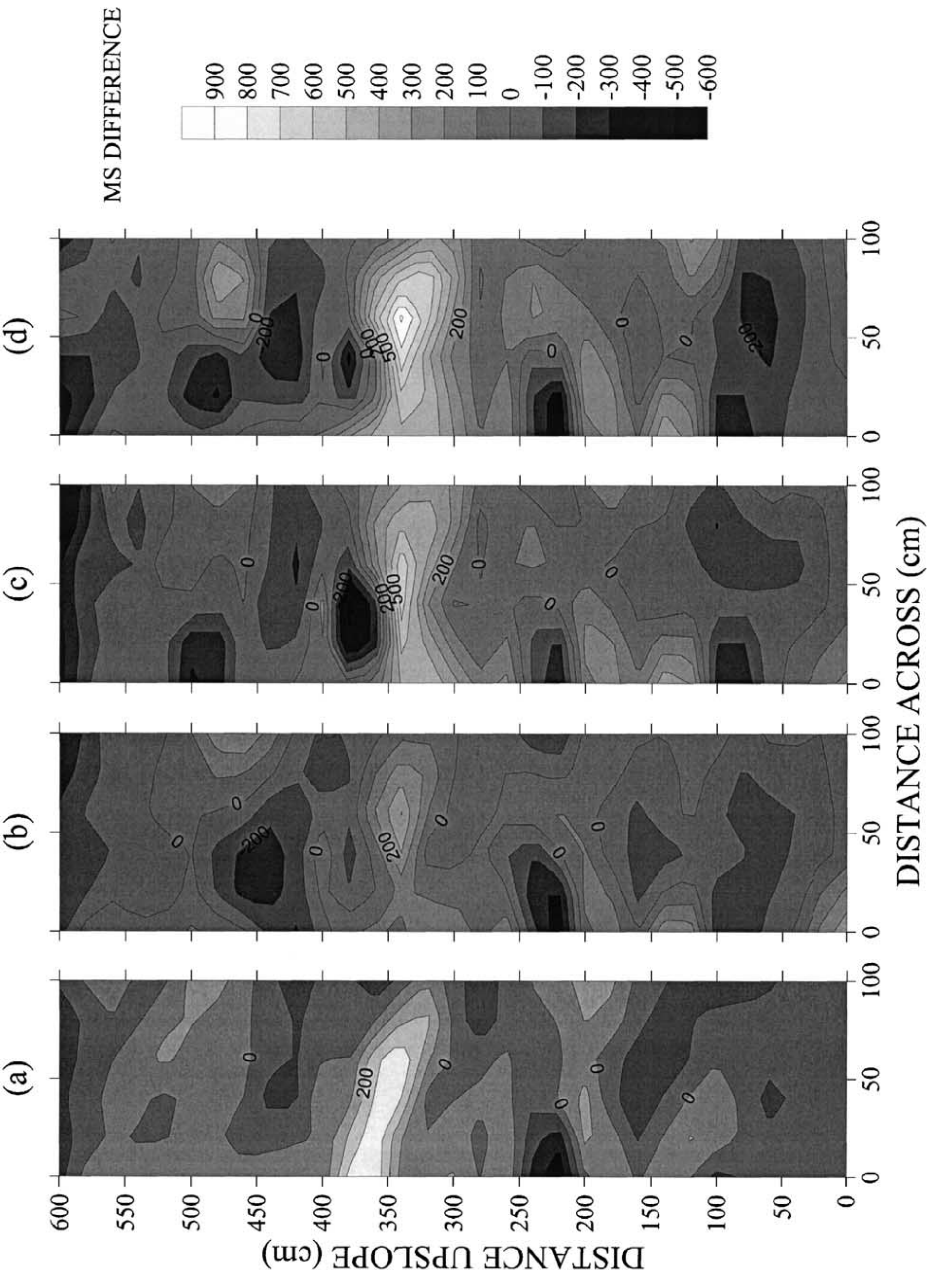
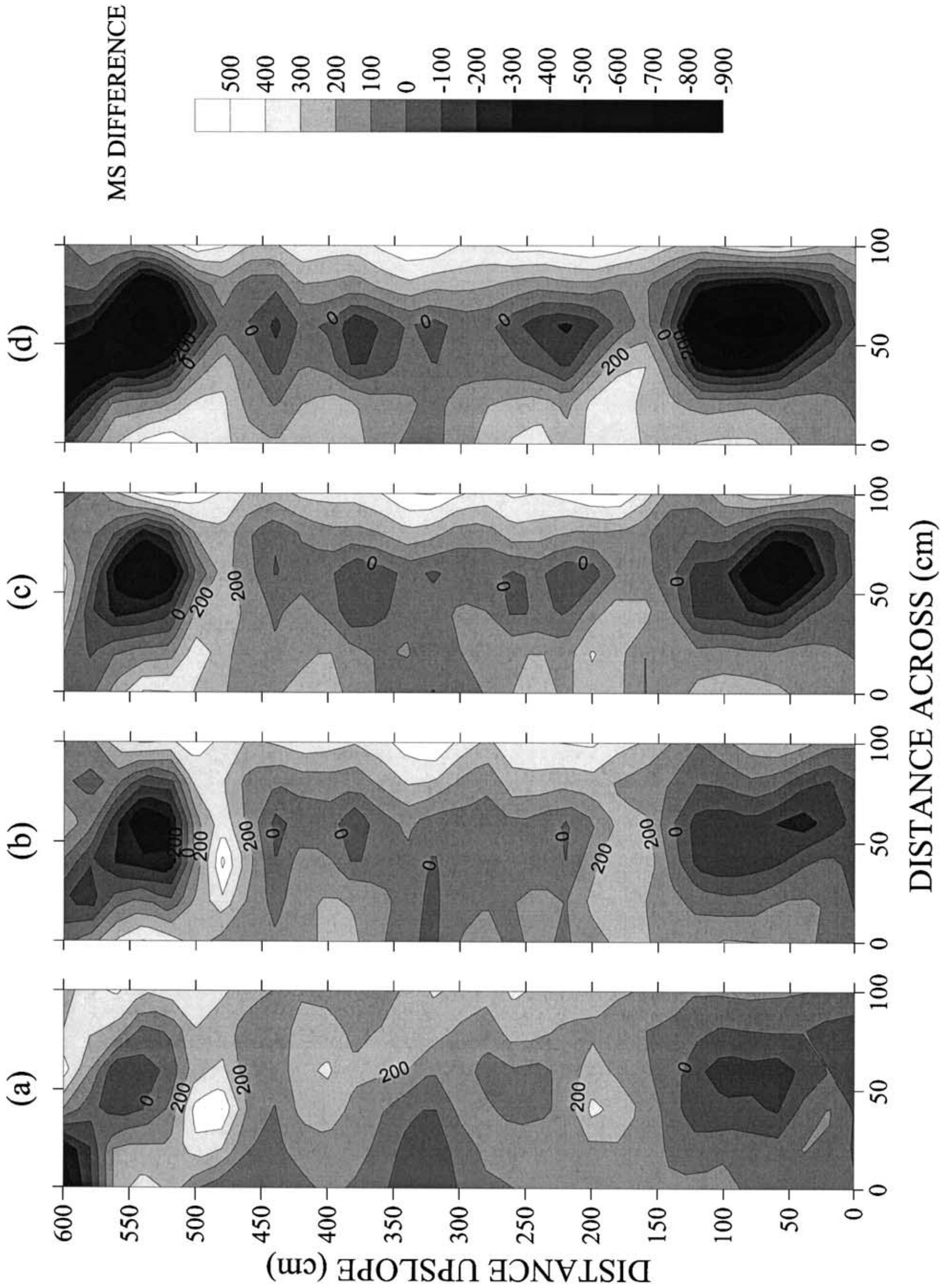
Fig. 2. Magnetic susceptibility (MS) differences between the initial values after mixing of tracer and after each treatment for replicate 1. Positive values are associated with areas of deposition and negatives values with areas of detachment. (a) Low inflow–low intensity, (b) low inflow–high intensity, (c) high inflow–low intensity, (d) high inflow–high intensity.


MS DIFFERENCE
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
(a)
(b)
(c)
(d)
DISTANCE ACROSS (cm)
0
50
100
DISTANCE UPSLOPE (cm)
600
550
500
450
400
350
300
250
200
150
100
50
0
200
500


MS DIFFERENCE
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
(a)
(b)
(c)
(d)
0
200
DISTANCE UPSLOPE (cm)
600
550
500
450
400
350
300
250
200
150
100
50
0
DISTANCE ACROSS (cm)
0
50
100

recorded and the magnetic tracer was separated from the soil using a magnet. Runoff samples were then flocculated and decanted and placed in the oven at 105 °C until they were of constant weight. The weight of dry magnetic tracer was also recorded to study the sediment to magnetic tracer ratio produced under the different treatments. This value was used to determine whether tracer moved in phase with the soil particles. After the four treatments were applied, the magnetic tracer was collected from the surface of plot 2 in increments of 20 cm along the plot. The amount of tracer from each 20-cm segment was measured. These values were regressed with the magnetic susceptibility readings to establish a relationship of the two variables.

3. Results and discussion

The initial magnetic condition after the tracer was placed into the soil in both replicates was different. For this reason, an increase or decrease in the magnetic signal of a particular grid in one replicate is spatially independent of the increase or decrease in the corresponding grid of the other replicate. Some results are presented for each replicate.

The average magnetic susceptibility of the soil without any addition of magnetic tracer (soil background) was approximately 40 (non-dimensional SI units) for all of the plots and the readings were consistent within the area. After mixing of tracer to a depth of 3 cm and a concentration 5%, the magnetic measurement value was increased by a factor of about 20. Plot 1 had values ranging from 750 to about 2000. These variations reflected the final distribution achieved after mixing, which presumably could be reduced with a more careful distribution. In any case, the reading in a specific grid cell after the tracer was placed into the soil was considered as the reference value or initial condition to study detachment and deposition. Detachment was associated with a reduction in the magnetic signal and deposition with an increase from the initial magnetic reading within each 20 × 20-cm grid on the plot.

After the soil was subjected to a low intensity (35 mm h^{-1}) and low inflow rate (4 l min^{-1}), only small changes were observed in the spatial distribution of magnetic susceptibility in plot 1 (Figs. 2a and 3a). A decrease in the magnetic signal was observed primarily in the upper part of plot 1 for replicate 2, which was associated with detachment caused by the initiation of runoff in that area. The sediment produced from there was either deposited along the plot or transported to the lower plot 2 to accumulate only a short distance beyond the influence of the rainfall (Fig. 4a). The final sediment balance on the lower part of plot 1 was low, indicating that soil was detached and deposited simultaneously on that area at essentially the same rate, which in turn suggests that the system was transport-limited. Average net soil loss under steady-state conditions for this treatment over the whole of plot 1 in both replicates was approximately 52 g m^{-2} for the sampling interval of 5 min (Fig. 5).

Fig. 3. Magnetic susceptibility (MS) differences between the initial values after mixing of tracer and after each treatment for replicate 2. Positive values are associated with areas of deposition and negatives values with areas of detachment. (a) Low inflow–low intensity, (b) low inflow–high intensity, (c) high inflow–low intensity, (d) high inflow–high intensity.

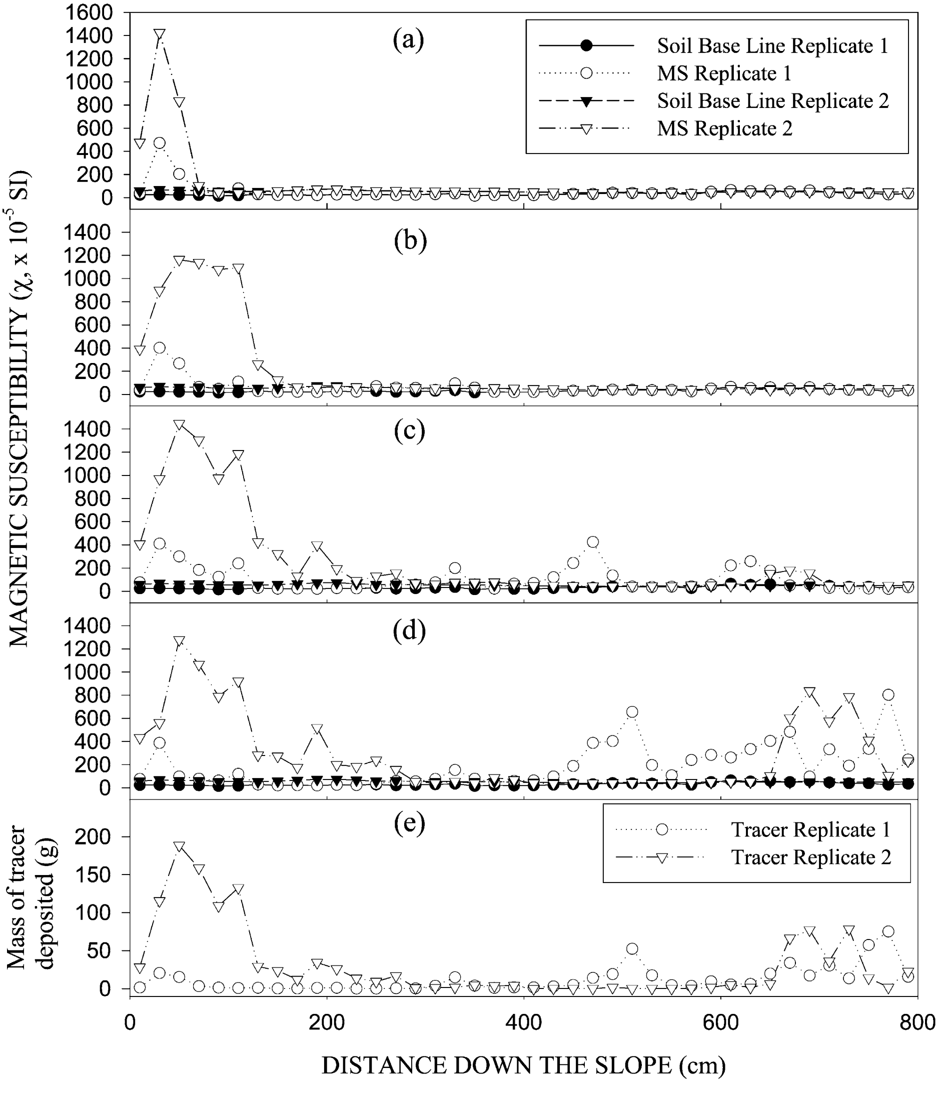


Fig. 4. Magnetic susceptibility values on the area of deposition after consecutive hydraulic treatments: (a) Low inflow–low intensity, (b) low inflow–high intensity, (c) high inflow–low intensity, (d) high inflow–high intensity. The bottom graph (e) indicates the amount of tracer deposited along the slope as physically measured after the high-inflow–high-intensity experiment.

The soil to tracer ratio of eroded sediment was approximately 5:1, meaning that under this condition the tracer was not in phase with the soil and more tracer was detached as compared to the soil than would be expected based on the initial concentration of 5%.

An increase in rainfall intensity (70 mm h^{-1}) with the same inflow conditions (4 l min^{-1}) caused a greater detachment in plot 1 (Figs. 2b and 3b). Incipient head cutting was

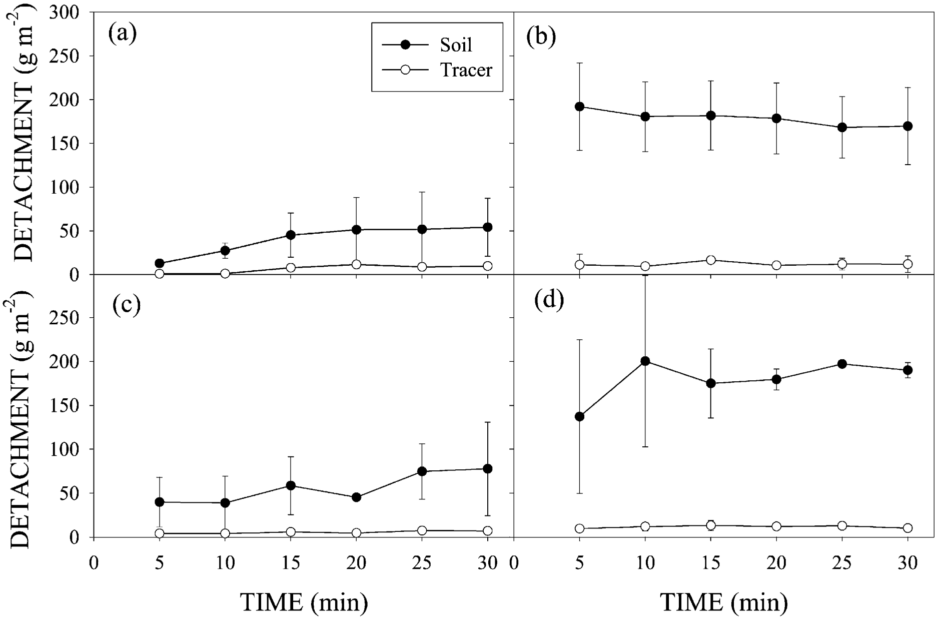
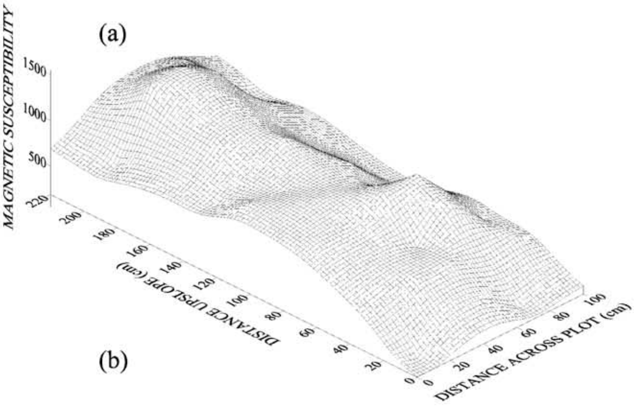


Fig. 5. Sediment and tracer detachment for the combination of two different rates of inflow water and two different rainfall intensities. (a) Low inflow–low intensity, (b) low inflow–high intensity, (c) high inflow–low intensity, (d) high inflow–high intensity.

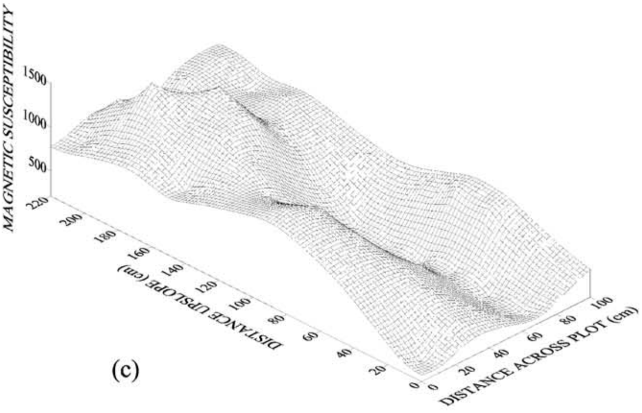
observed close to the outlet in plot 1 of replicate 2. The magnetic susceptibility in that area (the lower part of the plot) decreased by approximately 250 units, and a reduction in the signal of up to 500 was observed in the upper part of the same plot. The final balance of detachment and deposition in plot 1 indicated greater overall detachment. Deposition in plot 2 was most visible in the first 1–2 m (Fig. 4b). The average net soil loss for this treatment increased to approximately 172 g m^{-2}. The increase in the rainfall intensity caused greater soil detachment and transport. It was observed in the field that, apparently, the turbulence of the concentrated flow was significantly increased due to the impact of raindrops. Soil and tracer were eroded from plot 1 of both replicates at an average ratio of approximately 15:1, which is closer to the expected 20:1 ratio of the original mixture, but still less than the original 5%. This value remained fairly constant with time (Fig. 5).

When inflow rate was increased to 10 l min^{-1} and the intensity reduced to 35 mm h^{-1}, net soil loss was reduced to an average value of 66 g m^{-2} in plot 1 with a soil to tracer ratio of about 10:1. This condition lowered soil loss significantly, indicating the importance of rainfall in the processes of soil erosion not only by increasing detachment by splash, but possibly also by imposing turbulence to the flow which increased flow detachment (Nearing and Parker, 1994) and transport capacity. The soil to tracer ratio remained fairly constant, although it was less than that of the ratio of the originally mixed soil. Head cutting in plot 1 of replicate 2 increased significantly compared to the previous treatment with the lower inflow rate, enhancing the area of detachment in the lower part the plot. Visible areas of detachment were also observed for the same plot in replicate 1. Sediment was deposited

(a)


MAGNETIC SUSCEPTIBILITY
1500
1000
500
220
200
180
160
140
120
100
80
60
40
20
0
DISTANCE UPSLOPE (cm)
0
20
40
60
80
100
DISTANCE ACROSS PLOT (cm)

(b)


MAGNETIC SUSCEPTIBILITY
1500
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220
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120
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DISTANCE UPSLOPE (cm)
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80
100
DISTANCE ACROSS PLOT (cm)

(c)

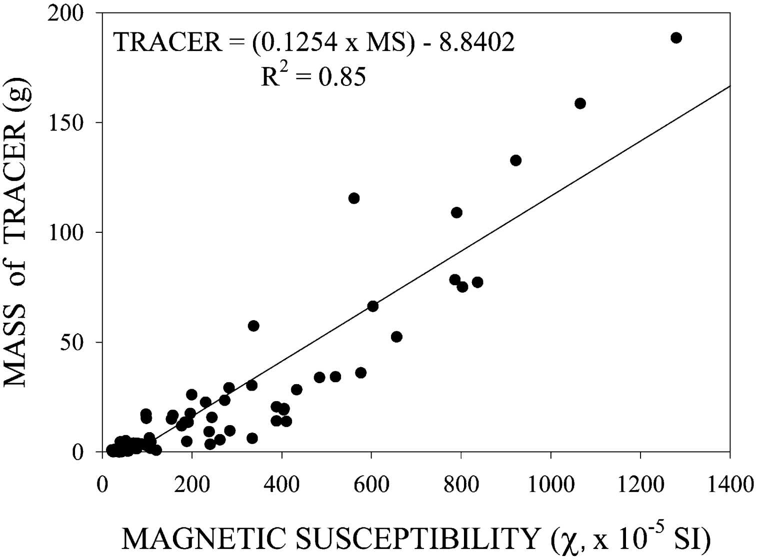

Fig. 7. Relationship between the amount of tracer deposited on the lower plot and the magnetic susceptibility readings.

in more extensive but well located areas of plot 2 (Fig. 4c). No significant deposition occurred between 3 and 6.5 m of plot 2 in replicate 2. This result has been reported by other researchers working with flumes of similar dimensions and more controlled conditions (Merten et al., 1999), but in this case deposition at the end of the plot was probably due principally to ponding behind the grass strip.

Conditions of high runoff (10 l min^{-1}) and high intensity (70 mm h^{-1}) produced a visible, well-defined rill by head cutting and concentrated flow in both replicates. Final magnetic susceptibility after this treatment was decreased by up to 800 units in localized areas (Figs. 2d and 3d). In replicate 1, the rill formed along the plot, while in replicate 2, it was formed from the lower plot end and moved upwards, resulting in the negative difference in magnetic values along the center line of the plot. The graph of magnetic susceptibility and field observations were consistent in terms of the spatial location of the rill (Fig. 6). Average soil loss with this last treatment increased significantly in relation to the previous treatment to a value of approximately 189 g m^{-2} min^{-1}, which was the greatest value for all studied treatments. The average soil to tracer ratio of the sediments eroded was approximately 16:1, which was consistent with time under steady-state conditions. In plot 2 of both replicates, deposition was significantly increased for this treatment in the lower part of plot 2 where water-flow was slowed by the presence of the grass strip.

In order to determine whether the measurement of the amount of tracer from the physical separation of the beads deposited on plot 2 corresponded to the measurement of

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Fig. 6. Spatial variation of magnetic susceptibility values in the lower part of plot 1 and a visual correlation with the presence of a rill. (a) Initial condition, (b) final condition after low inflow and high intensity, (c) location of a rill.

magnetic susceptibility, we regressed those two variables as measured after the final treatment. The two variables were linearly related with a coefficient of determination, r^2, of 0.85 (Fig. 7). This result indicates that magnetic susceptibility measurements accurately reflected the distribution of deposition on the plot.

Soil and tracer did not move in phase during this experiment. In all cases, the ratio of the eroded tracer as collected from the end of plot 1 was greater than the original 5% concentration of the tracer in the soil. This indicates that beads were preferentially moved relative to soil particles or aggregates under this system. Also, this discrepancy was not constant between treatments. The ratio was much closer to the original concentration when sediment loads were high, which was the case when rainfall intensities were high. In any case, tracer was preferentially eroded as compared to the soil sediments. Density of soil aggregates and sediments is expected to be greater than the density of about 1.2 g cm^{-3} as reported for the tracer evaluated (Ventura et al., 2001). This condition may be partially responsible for the greater proportional loss of tracer as compared to soil sediments. Therefore, we suggest testing a wider range of sizes and densities of tracers to correctly determine detachment and deposition under varying conditions of rainfall intensity and runoff rate.

4. Conclusions

The methodology used in this experiment allowed us to qualitatively study soil redistribution on a plot due to water erosion. The study outlines the potential for an important tool for monitoring temporal changes in the redistribution of sediment during the erosion process. The initial enhancement of “soil magnetism”, caused by placing a magnetic tracer mixed to a depth of 3 cm and 5% concentration by weight, increased on the order of a factor of 20. From this initial condition, areas of detachment and deposition of the tracer were clearly identified using magnetic susceptibility readings. Areas of tracer detachment corresponded to areas were the magnetic signal decreased. In the plot designed for accumulation to occur, deposition of tracer correlated well with the magnetic susceptibility readings. This indicates that once the initial conditions are measured, a quantitative estimate of either detachment or deposition may be obtained using this non-intrusive technique if the soil/tracer ratio of sediments is known. However, we found that a preferential sediment sorting was observed, which enriched the tracer concentration in the sediment, especially for low rainfall intensities, indicating that a wider range of sizes and densities of the tracer will be required if quantitative measures of erosion rates are to be obtained via this methodology.

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